# Laser Excited Single Crystal Phosphor Waveguide for High Power Applications

**Y.P. Chang[1], Lion Wang[1], Kirk Huang[1] Kenneth Li[2]**

[1]Taiwan Color Optics, Inc., Taichung City, Taiwan
[2]Optonomous Technologies Inc., Agoura Hills, CA 91301, USA
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**ABSTRACT**

*Single crystal phosphor has been developed with superior material performance for conversion of blue laser light into yellow visible light providing high efficiency, high temperature operation, and operation in a larger volume waveguide form for ease of heat sinking. This paper presents an end-pumped structured crystal phosphor waveguide design such that the volume of laser absorption and heat dissipating surfaces are both larger with a small output cross-section for small etendue operations. Preliminary samples have been fabricated with expected results. Several structures and measurement results will be presented.*

## 1 INTRODUCTION

LEDs can have high output power only with large emission area as the brightness of LEDs is not high enough. For high brightness applications, laser phosphor system has been developed in the last 10 years using mostly silicone, ceramic [1] and glass, phosphors for low power applications. For higher power systems such as projectors, phosphor wheels are used so as to dissipate the heat in a larger area, allowing the operating temperature to be below the damage and droop threshold of the phosphor material. For silicone phosphor, the outputs are usually limited by the organic bonding materials. This paper presents a static, without a rotating wheel, high power laser excited crystal phosphor waveguide system in which the crystal phosphor has a very high damage and drooping threshold temperature. Using 2 laser diode arrays, a total of 170 W of blue laser light is focused into an area of smaller than 2 mm in diameter, giving a power density of over 54 W/sq. mm., which is limited by the available laser power. It is expected to increase in the near future with higher power laser sources, development of homogenizing and diffusing optics at the input would greatly increases this threshold by several folds. For projector applications, this high-power static crystal phosphor system can replace the current phosphor wheel, in most case, directly without redesign of the other projector components in terms of mechanical, optical, and electronics.

## 2 CRYSTAL PHOSPHOR WAVEGUIDE

There are many advantages in which the phosphor wheel is replaced by a static phosphor especially for very high-power operation. For a phosphor wheel, it will be difficult to heat sink the wheel properly as it is away in motion. On the other hand, the static phosphor can be mounted on a heavy heat sink with fins, heat pipes, vapor chamber, fans, etc. A large amount of heat can be dissipated when the phosphor plate can be mounted onto the heat sink in a permanent fixture. As the power level continues to increase, the amount of heat generated in the small focused area can also be very challenging for heat dissipation. As a result, having a large heat dissipating area will be required for very high-power applications. Figure 1 shows an example of a crystal phosphor waveguide system.

**Figure 1 – Crystal Phosphor Waveguide**

The most common type is the Ce:YAG, which emits yellowish light. When mixed with the stray blue light, white light output is obtained. The other common type is the Lu:YAG, which emits slightly greenish light. This material is suitable when a single green output is required with higher overall conversion efficiency compared to that of the Ce:YAG materials. The spectral characteristics of these materials are shown in Figure 2.

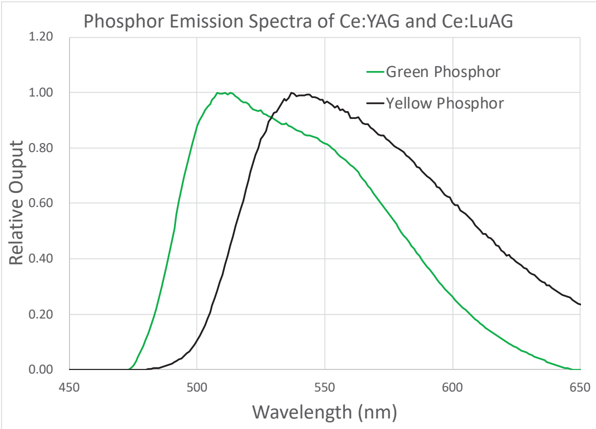


**Figure 2 – Emission Characteristics of Yellow and Green Phosphors**

## 3 THE GROWTH OF CRYSTAL PHOSPHOR

Contrary to other phosphor materials including silicone phosphor, ceramic phosphor, or glass phosphor, crystal phosphor is formed by growing the crystal at high temperature over a molten liquid of phosphor and carrier material where the atoms form a regular pattern and is transparent to certain wavelength of light. For yellow light output with absorption of the blue light, a Ce3+:YAG material system is used. The growth of single crystal phosphor (Ce3+: YAG) is carried out by Czochralski (CZ) method. The CeO2, Y2O3, and Al2O3 with a purity of 99.999% are used as raw materials. They are weighed to the correct proportion, mixed in the crucible, and melted down by the radio frequency heater without any external contaminations. A seed crystal with predetermined orientation of the single crystal of the single crystal phosphor to be grown is mounted on a rod and dipped into the molten materials. By controlling the temperature gradient, rotation speed and pulling rate, the Ce3+: YAG single crystal phosphor is being grown and produced as shown in Figure 3, which is call a preform. Throughout the growing period, high purity N2 gas is used to prevent the oxidation of crucible.

**Figure 3 – Photo of a Crystal Phosphor Preform**

After the preform is grown, it will be saw-cut into wafers of the desired thicknesses. These wafers will then be fine polished to high gloss or rough polished providing features on the surface, which has special optical properties. One side of the wafer is metalized such that the die after cutting can be soldered onto the heat sink as shown in Figure 1(b). For static phosphor, cutting the wafer in both the x- and y- directions can produce dies in various sizes, e.g. 3 mm by 3 mm. For a typical crystal phosphor wafer of diameter in the range of 60 mm, total number of dies can be in the range of a few hundred dies. For other applications, crystal waveguides can be fabricated where the wafer is cut into rods and polished in all sides producing a waveguide structure. Such structures are usually used for side excitation or end excitation with the visible light exiting from one end of the crystal phosphor waveguide.

## 4 CRYSTAL PHOSPHOR LIGHT SOURCES

As mentioned earlier, there are two basic configurations for crystal phosphor light sources, the phosphor plates and phosphor waveguide as shown in Figure 1, which is simply a length of crystal phosphor polished in all sides. Figure 4 shows two configurations in which the crystal phosphor waveguide can be excited by one or more laser diodes. The input surfaces for laser excitation are coated with blue transmitting layers and the output surface is coated with blue reflective layers. The rest of the surfaces are coated with high reflective coating. Due to the high reflective index of the crystal, which is about 1.82, the percentage output is relatively low and as a result, various methods have to be implemented, including CPC's, photonic surfaces, laser scribed surfaces, etc., so as to increase the output coupling efficiency.

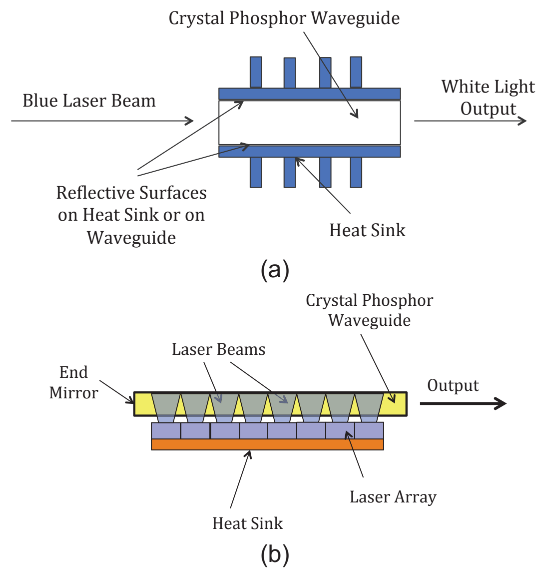


**Figure 4 – End and Side Excitation Light Sources**

Figure 5 shows the structure of the crystal phosphor waveguide system with high refractive coupled to a lower refractive index CPC such that the total internal reflection between the crystal phosphor waveguide is lowered increasing the output efficiency of the system. One disadvantage is that the attachment of CPC to the waveguide is usually done by using organic optical epoxy, which would have potential long-term stability and life time issues. This would be acceptable for low power applications, but will not be suitable for power levels suitable for digital cinema projectors.

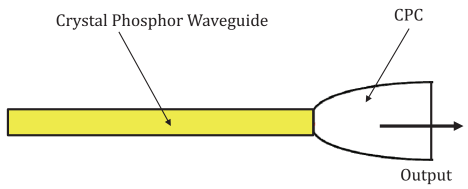


**Figure 5 – Increase Output Efficiency using CPC**

Figure 6 shows the structure of the crystal phosphor waveguide system with a structured output surface including rough polish, laser scribed, or a photonic structure such that the light from the crystal phosphor waveguide would see layer of material whose refractive index is higher than that of air. Again, the total internal reflection between the crystal phosphor waveguide and this structured layer is lowered increasing the output efficiency of the system

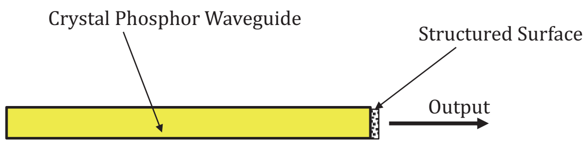


**Figure 6 – Increase Output Efficiency using Structured Surface**

Figure 7 shows a patent pending structured volume between the crystal phosphor waveguide and air. The structure volume allows the graduate transition of refractive index from that of the crystal phosphor to that of the air. This allows the light to be coupled into the air with higher efficiency.

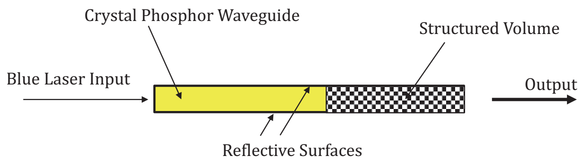


**Figure 7 – Increase Output Efficiency using Structured Volume**

## 5 PRELIMINARY RESULTS

Two samples of the crystal phosphor waveguide had been fabricated with dimensions of 3 mm x 3 mm x 20 mm. Output the length of 20 mm, 15 mm of which is made with the structured volume, which is one of the possible structures in this study. A reference waveguide without the structure is also made for reference. The structured waveguide was place at the center of the integrating sphere and excited by a blue laser beam. The output yellow light output was measured. Using the measurement system, the output from the reference waveguide was also measured. It was found that both emits the same amount of yellow light showing that the structured waveguide has the same emission property of the reference waveguide. The structured waveguide was then placed at the input port of the integrating sphere collecting only the light exited from the 3 mm x 3 mm output surface. The efficiency was measured to be 170.5 lumens/W and 177.5 lumens/W. These shows the consistency of the system and sufficiently high efficiency for practical applications.

More samples are being fabricated using various structures and higher conversion efficiency and better far-field distribution are expected.

## 6 CONCLUSION

A crystal phosphor waveguide light source is described with preliminary results presented. It is expected that the system is suitable for high power operation with larger area for heat sinking. Further studies are being perform with various structures and future results will be presented.

## REFERENCES

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